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Green Solutions: Microbial Consortiums for Soil Restoration and Maximize Production in Agriculture

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ABSTRACT
Consistent increase in the food demand has resulted in overexploitation of farmlands worldwide. Not only do nutrients get exhausted after every crop cycle but due to the use of chemical fertilizers, pesticides, and insecticides, soil gets heavily polluted. Almighty God has placed precious genes in a few microbes and sent them as tiny angles, capable of pollutant clean-up, and soil restoration in a sustainable manner. These microorganisms including bacteria, fungi, and algae can degrade and detoxify injurious compounds from the soil called Bioremediation. Pollutants such as petroleum hydrocarbons, heavy metals, pesticides, and industrial chemicals present in soils, waterways, and industrial sites can be transformed into less toxic or non-toxic forms by certain bacteria and fungi. Some fungi called Mycorrhiza, associate with plant roots in symbiotic ways that benefit the fungus and the plant in different ways. These fungi help the host plants better absorb water and nutrients, particularly phosphorus. Mycorrhizal partnerships are beneficial in agricultural practices because they improve plant development and overall soil health. Rhizobium, Azospirillum, Actinomycetes, Trichoderma, Bacillus, and Pseudomonas are some key microbes that actively participate in the bioremediation process. The functions and uses of microorganisms in soil restoration are summarized in this review along with the formulations of the microbial consortium utilized so far. This study can be utilized to formulate a better, crop-specific, and locality-specific consortium for maintaining soil health and maximizing yield.
Keywords: *Bioremediation, Mycorrhiza, Rhizobium, Soil restoration, Trichoderma*

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INTRODUCTION

Good soil health is a preliminary requirement for agriculture. By prioritizing soil health in cultivation practices, farmers can ensure sustainable and productive agricultural systems, protect the environment, conserve natural resources, and contribute to global food security. Not only does the soil serve as a reservoir of essential nutrients that are necessary for plant growth like; macronutrients (such as nitrogen, phosphorus, and potassium), and micronutrients (such as iron, zinc, and manganese), but healthy soils with good structure and organic matter content improve water holding capacity, making water accessible during dry periods and reduces the risk of waterlogging during heavy rainfall. Soils rich in organic matter contribute to carbon sequestration, as organic matter holds carbon in the soil for an extended period [1].

Moreover, soil structure, porosity, and nutrient availability influence root growth, and oxygen availability, essential for root health and the functioning of beneficial soil organisms. An active population of beneficial soil microorganisms contributes to natural disease and pest suppression, thereby, reducing the need for chemical interventions [2]. A balanced soil ecosystem helps maintain a natural balance between pests and beneficial organisms, promoting sustainable cultivation practices [3]. Hence, healthy soils with proper water-holding capacity, oxygen, and nutrient availability, support plant growth and enhance vegetation cover, which helps regulate local climate conditions [4, 5].

In India, Land scarcity, declining per capita land availability, economic pressure on land, land tenancy, poverty, and population growth are some underlying societal factors of soil degradation. Earthquakes, tsunamis, droughts, avalanches, landslides, volcanic eruptions, floods, tornadoes, and wildfires are a few examples of natural causes. Land clearance and deforestation, incorrect farming methods, improper management of industrial effluents and wastes, excessive grazing, negligent forest management, surface mining, urban sprawl, and commercial/industrial development are all causes of human-induced soil degradation [6]. Soil degradation occurs due to various factors such as erosion, nutrient depletion, pollution, compaction, and loss of organic matter, over time [7]. In the Mediterranean part of Europe soil erosion and desertification are most likely to occur. These soils are subject to several types of physical,

chemical, and biological deterioration. The natural capital of soils is under threat from unsustainable management practices and climate change. These shallow soils are under intense pressure from climate change, population growth, and quick changes in land use [8].
Regular soil restoration is a must for improving the quality and health of degraded or damaged soil, which involves implementing various techniques and practices to enhance soil fertility, structure, and overall ecosystem function [9, 10]. The restoration of soil typically involves several practices like; soil assessment, erosion control, soil organic matter management, nutrient management, soil conservation practices, water management, biodiversity promotion, sustainable land management, and regular monitoring and maintenance. The ultimate aim is to improve soil fertility, ecosystem resilience, and agricultural productivity while minimizing environmental impact and preserving natural resources [11, 12].

Role of Microbes in Soil Restoration

Microorganisms in the soil are crucial to the nutrient cycles, which are the basis of all life on Earth. The bacteria in fertile soil are abundant. One gram of soil may contain hundreds of millions to billions of bacteria. The bacteria are the most prevalent soil microorganisms, followed in decreasing order by actinomycetes, fungi, soil algae, and soil protozoa. If agricultural productivity is to satisfy the demands of a growing global population, a greater understanding of soil microbiology is vital [13].
Due to its eco-friendly, effective, and economical benefits, PGPR application for soil bioremediation and cereal growth enhancement has recently attracted a lot of attention. So, in dry conditions, bacteria like Arthrobacter, Azotobacter, Bacillus, Enterobacter, Pseudomonas, etc., have demonstrated their effectiveness as plant growth boosters and soil quality remediators [14]. As our awareness of the major signal molecules involved in these interactions and our understanding of the interacting features between plants, bacteria, and soil has grown, PGPR's role in contemporary agriculture as biocontrol, biofertilization, and bioremediation agents has become clear [15].
Microorganisms play a crucial role in soil restoration by contributing to nutrient cycling, organic matter decomposition, soil structure improvement, and disease suppression [16]. Soil microorganisms are in charge of the majority of biological transformations and propel the growth of stable and labile carbon (C), nitrogen (N), and other nutrient pools [17]. They facilitate the formation of the vital skin of the earth called soil, the home to all plant communities [18]. They may be free living in soil or rhizosphere or maybe in association with plants as exo or endophytes [19].
Microalgae and bacteria that stimulate plant development are examples of helpful microorganisms that excel in reviving the fertility and health of the soil. Combining these microbes can help recover polluted and deteriorated soils. Such microbial consortia must have the ability to maximize positive impacts on soil health and increase the production of substances that promote plant development [20, 21].
The native bacteria’s ability to digest these contaminants is limited, and the process will take time. As a result of their changed metabolic pathways, genetically modified organisms (GMOs) can catalyze the degradation process by causing the over-secretion of a variety of biomolecules that support the bioremediation process [22]. Single microbe created through Genetic engineering techniques may be able to break down a variety of xenobiotics due to its capacity to integrate several genes involved in xenobiotic degradation. GMOs can be created using a variety of molecular techniques, including biolistic transformation, electroporation, conjugation, horizontal transfer of bacterial DNA molecular cloning, and protoplast transformation [23, 24]. The time needed for remediation is reduced by the transfer and production of new genes with high degrading capability. By expressing genes contained in the bacterial plasmid, engineered microorganisms could remove several chemicals, including toluene, octane, naphthalene, salicylate, and xylene [25].
One of the most effective bioremediation techniques for increasing the effectiveness of pollution removal is the employment of bacteria with both pollutant-degrading and plant growth-promoting capabilities [26, 27]. The multiple functions of PGPB, including biofertilization of soil, biocontrol of pathogens on plants, biostimulation of plant growth, and biodegradation of pollutants, all promise to increase the effectiveness of phytoremediation of organic pollutants [28, 29, 30]. Some of the key microorganisms commonly used for soil restoration are discussed here in detail.
Viruses affect the dynamics of food webs, carbon and nutrient cycling, and microbial mortality because they are prevalent members of microbial communities. Recent years have shown that the variety of viruses in the environment is far more than that which can be deduced from known viruses, the majority of which are pathogens of humans and other species that are significant to humans. More than 108 virus particles per gram of soil may be present in soils, and these diverse viruses can have a range of effects on plant development. Plant diseases that are transmitted through the soil can clearly have negative impacts. These plant viruses can live alone or in conjunction with other microbes or nematodes, which are vector organisms that live in the soil. Other viruses have the ability to infect soil microorganisms, which can impact the microbial functioning of the soil [31-37].

Some of the key microorganisms commonly used for soil restoration are discussed here in detail.

Mycorrhizal fungi:

These beneficial fungi form symbiotic relationships with plant roots, forming mycorrhizal associations. They help plants absorb nutrients, especially phosphorus, from the soil. Mycorrhizal fungi also enhance soil aggregation, improve water-holding capacity, and provide resistance against soil-borne pathogens. Mycorrhizal hyphae have several important tasks in soil, including improving plant access to nutrients, particularly phosphorus, allowing plant access to water in water-scarce situations, safeguarding soil organic matter, and boosting disease resistance. Mycorrhizas can therefore have an impact on economic gains due to the direct and indirect impacts they have on plants that are connected to the chemical, physical, and biological elements of soil fertility. The existence of mycorrhizas is essential to many soil processes and during soil management, their role must be taken into consideration [38]. The mycorrhizal fungus known as arbuscular mycorrhiza produces the bulk of the root cells and creates odd structures (arbuscules) inside the cell. The host plant serves as the source of food for the arbuscular mycorrhiza-forming fungus, which feeds on the plant's cells without harming the host. The real locations of the nutrient exchange between the fungus and plants occur within these cell structures. Extracellular networks that penetrate the surrounding soil in all directions, reach areas with very low nutrient concentrations and make PO_4^{-3} and NO_3^- available to the plant as food and other nutrients [39]. Because of the advantages to their symbiotic partners, arbuscular mycorrhizal connections are crucial in the repair of damaged ecosystems. In addition to assisting with plant establishment and survival in POP-contaminated soil by shielding plants from POP phytotoxicity, arbuscular mycorrhizal fungi also promote soil bioremediation by enhancing soil structure and telluric microbial activity [40]. The arbuscular mycorrhizal fungus also aids in the bioremediation of soils contaminated with Heavy Metals [41].

Through a variety of potential mechanisms operating at various scales, arbuscular mycorrhizal fungi (AMF) can aid in the ecological restoration of mining-affected areas. These mechanisms include enhancing host plant mineral uptake and tolerance, enhancing soil structure and quality, and assisting in maintaining ecosystem stability and functioning. Significantly better plant survival, development, and nutrition, as well as better soil structure and quality and more plant re-establishment, are all benefits of AMF [42]. Arbuscular mycorrhizal fungus (AMF) serve as a soil health indicator due to their involvement in soil aggregation and ecological or land restoration [43]. Arbuscular mycorrhizal fungi are responsible for metal adsorption on the fungal surface and immobilization in the soil by glomalin to neutralize heavy metal pollution. The hyphae of AMF participate in the distribution of heavy metals by chelating and sequestering HMs in their fungal structure, which is one of the tolerance mechanisms that involve the direct participation of fungi to create a physical barrier to HMs entering plants [44].

The idea that biochar and AMF have the potential to be essential tools for managing agroecosystems has been investigated by Gujre *et al.* [45]. Different aspects and restrictions of combined applications of biochar and AMF (BC + AMF), mechanisms of interaction between biochar and AMF, effects on plant growth, and challenges and future opportunities of BC + AMF applications were just a few of the broader perspectives of various agronomical and environmental backgrounds that were discussed. Despite the potential advantages, it is still far from clear how BC + AMF operates and behaves in soil.

Rhizobium bacteria:

Rhizobium species form symbiotic relationships with leguminous plants, such as peas, beans, and clovers. They colonize the root nodules of these plants and convert atmospheric nitrogen into a form that plants can utilize, a process known as nitrogen fixation. Rhizobium bacteria help enhance soil fertility and reduce the need for synthetic nitrogen fertilizers. Rhizobium bacteria play a vital role in soil restoration and agricultural ecosystems, particularly in the context of nitrogen fixation and plant growth [46].

Rhizobium bacteria have a unique ability to form symbiotic relationships with leguminous plants, such as beans, peas, and clovers. These bacteria reside in nodules on the plant's roots and convert atmospheric nitrogen (N2) into a form (ammonia - NH3) that can be utilized by plants. As a result, Rhizobium bacteria enhance soil fertility by making nitrogen available to the plants, which is an essential nutrient for their growth. The process of nitrogen fixation by Rhizobium bacteria contributes to increasing the soil's nitrogen content. This enrichment benefits not only the host leguminous plant but also nearby plants that can absorb the released nitrogen, leading to improved overall soil fertility. Reduction of the dependency on synthetic nitrogen fertilizers helps in mitigating the negative environmental impacts associated with excessive fertilizer use, such as nutrient runoff and greenhouse gas emissions [47].

Rhizobium promotes soil health by stimulating root development and root nodulation in leguminous plants. The nodules formed by the bacteria on the plant roots also aid in soil aeration and aggregation. Improved soil structure enhances water infiltration and retention, reduces erosion, and provides a favorable environment for beneficial soil organisms [48]. Drought- and salinity-tolerant Actinobacteria with several plant growth-promoting characteristics may be able to boost lucerne growth in high salt circumstances, in the presence or absence of symbiotic rhizobial bacteria. To improve plant growth, health, and productivity in salty soils, actinobacteria are therefore appropriate biofertilizers in the formulation of agricultural goods, a crucial alternative for contemporary agriculture and sustainable development [49].

Some strains of Rhizobium bacteria possess plant growth-promoting properties and have been found to suppress certain soil-borne plant pathogens. This biological control mechanism can contribute to reducing the prevalence of plant diseases and enhance overall crop health. Rhizobium inoculation has been used as a biotechnological tool in soil restoration efforts, especially in degraded or barren areas [50]. Introducing Rhizobium bacteria to such areas, along with compatible leguminous plants, helps in initiating a process of ecological succession, leading to the establishment of a more diverse and fertile ecosystem. The association of Rhizobium bacteria with leguminous plants promotes plant growth, which, in turn, contributes to increased carbon sequestration in the soil. This can help in mitigating the effects of climate change by reducing the concentration of carbon dioxide in the atmosphere [51].

Rhizobia are advantageous for cleaning up polluted soils because they have the biochemical and ecological ability to break down organic contaminants and are resistant to heavy metals. Additionally, rhizobia promote the growth and activity of other bacteria that degrade organic matter, hence reducing the concentration of contaminants [52]. Multiple rhizobial strains work together synergistically to promote plant development and increase the availability of contaminants like heavy metals and persistent organic pollutants. The advantageous interaction between plants and rhizobia offers a viable remediation approach because phytoremediation has some limitations [53]. Based on the Rhizobium-legume symbiosis, many methods and tactics are being used to increase the bioaccumulation capability and bioremediation of heavy metals. Along with increasing the bacterial potency for ingesting heavy metals, co-inoculation of plants with rhizobia and heavy metal-resistant plant growth-promoting rhizobacteria (PGPRs) offers significant benefits for promoting plant growth. An intriguing and important alternative has emerged in the application of bacterial genetic/molecular engineering techniques, notably for the symbiotic connection Rhizobium-legume. It provides a larger capacity for the breakdown of different metal pollutants to support the cleanup of polluted soil [54]. One element to take into account for restoring ultramafic soils in Barro Alto regions where mining activity has deteriorated them is the presence of Paraburkholderia in symbiosis in nodules from Mimosa plants naturally occurring in ultramafic soils [55]. An extensive variety of bacteria from the root zone (Plant Growth Promoting Rhizobacteria) viz., Actinomycetes, Aerobacter, Arthrobacter, Azospirillum, Azomonas, Azotobacter, Bacillus, Bradyrhizobium, Clostridium, Cellulomonas, Derxia, Flavbacterium, Micrococcus, Mycobacterium, Klebsiella, Pseudomonas, Serratia, Rhizobium, etc., may be applied as biological agents to assist in the biosorption of soil pollutants, which include heavy metals and organic compounds [56]. The phytoremediation potential of a symbiotic system made up of the Cd-tolerant pea mutant and a few carefully chosen Cd-tolerant microorganisms, such as the plant growth-promoting rhizobacterium Variovorax, the nodule bacterium *Rhizobium leguminosarum*, and the arbuscular mycorrhizal fungus *Glomus sp.,* was thoroughly investigated. Legumes cultivated in Cd-contaminated soil were driven to develop and accumulate Cd by a microbial consortium made up of several micro-symbionts (PGPR, rhizobia, and AMF). Under the stress circumstances brought on by Cd toxicity, this system demonstrated great symbiotic potential, permitting Cd tolerance and accumulation. The findings highlighted how legume plants may be employed for phytoremediation if a group of symbiotic microbes are present and successfully integrate with the genotype of a plant that is HM-tolerant [57].

Legumes with associated rhizobia form a unique group for healthy soil regeneration, including mine areas. They reduce the mobility of heavy metals and stop their spread to other ecological compartments. The intricate interactions between legumes and rhizobia include metal-tolerance or metal-resistance mechanisms, plant growth-promoting abilities, nitrogen-fixing capacity, generation of phytohormones, and phosphorus solubilization. By boosting legume yields, heavy metal accumulation in legumes, and nitrogen and phosphorus content in both legumes and contaminated lands, these rhizobium features most likely with rhizosphere PGPB and mycorrhizal fungi enhance legume growth in heavy metal polluted soils [58]. Yu *et al.* found that the use of *Pongamia pinnata* during a 2-year phytoremediation of a V-Ti magnetite tailings dam resulted in better soil conditions. Phosphatase, urease, and invertase enzyme activities in the soil were greatly increased, indicating improved soil health and microbial activity. Particularly those belonging to the phylum Proteobacteria, microbial populations grew with high -diversity and showed a significant association with several environmental parameters, such as N and P in the soil [59]. Overall, Rhizobium bacteria are crucial in restoring soil fertility, supporting sustainable agriculture, and playing a role in environmental conservation efforts. Their ability to fix nitrogen and promote plant growth makes them valuable allies in enhancing soil health and productivity [60].

Azospirillum bacteria:

Azospirillum species are free-living, nitrogen-fixing bacteria that promote plant growth and development. They colonize the root surface and release plant growth-promoting substances, including auxins, gibberellins, and cytokinins. Azospirillum bacteria enhance nutrient uptake, increase root biomass, and improve overall plant vigor. Reclamation of saline-sodic soil in dry areas is very important. For free remediation of saline-sodic soils, the utilization of Azospirillum inoculation with eco-friendly organic wastes was examined. It was discovered that for the improvement of saline-sodic soil, Azospirillum should be added to the wasted grain. Compost is not as efficient in improving and restoring saline-sodic soil fertility [61].

Azospirillum plays a significant role in bioremediation, which is the use of living organisms to clean up or degrade pollutants from contaminated environments. In the context of bioremediation, Azospirillum, as a beneficial soil bacterium, contributes to the process in several ways. Azospirillum can enhance the availability of nutrients, such as nitrogen and phosphorus, in contaminated soil. This increased nutrient availability can support the growth and activity of other microorganisms involved in bioremediation, facilitating the degradation of pollutants. Perennial plant development is not possible in the barren soil of the desert. In the southern Sonoran Desert, seedlings of the gigantic cardon cactus were planted, inoculated with the bacteria *Azospirillum brasilense* Cd, and cultivated for 18 months under nursery conditions suited to slow-growing cacti. The use of compost with *A. brasiliense* Cd was crucial for seedling development in bare soil [62].

Azospirillum produces a variety of enzymes that can break down complex organic pollutants present in the contaminated soil. These enzymes, such as dehydrogenases, oxidases, and hydrolases, help in the transformation and mineralization of organic contaminants into simpler and less harmful substances. Strains of the bacterium Azospirillum are capable of destroying contaminants including phenol, benzoate, and hydrocarbons like crude oil. The differential responses of several Azospirillum strains to aromatic chemicals suggest some specificity and variety within the genus. Azospirillum is known to produce biosurfactants, which are molecules that can solubilize hydrophobic (water-repellent) contaminants, such as certain petroleum hydrocarbons. By increasing the solubility of these pollutants, biosurfactants make them more accessible to microbial degradation [63].

Azospirillum can colonize plant roots, forming beneficial associations with plants. This can enhance the plant’s ability to take up and accumulate certain contaminants, making them more amenable to phytoremediation processes (where plants are used to extract, stabilize, or degrade pollutants). Azospirillum is naturally adaptable to different environmental conditions, including those found in contaminated soils. Its ability to survive and thrive in such environments makes it a potential candidate for use in bioremediation strategies. Despite having high total phosphorus (P) levels, the bioavailable inorganic phosphorus (Pi) levels in most farmed soils are inadequate. Using plant-growth-promoting rhizobacteria (PGPR), like; ***Azospirillum*** is a sustainable way to use phosphorus. *A. brasilense* can increase root hair formation, acid phosphatase activity, and Pi transporter expression levels, which improves the plant's ability to absorb Pi and makes it more tolerant to a lack of it [64].

Fluorescence in situ hybridization and confocal laser scanning microscopy showed that *A. brasilense* NH is capable of colonizing durum wheat roots endophytically when exposed to salt stress. As a result, the salt-tolerant rhizobacterium *A. brasilense* NH may be able to successfully offer either alone or in combination with extracts of *Ulva lactuca* a viable solution to overcome salt inhibition, which is a significant risk impeding productive wheat cultivation on arid saline soils [65]. In some cases, Azospirillum can engage in co-metabolism, where it degrades certain pollutants indirectly by producing metabolites or enzymes that break down the contaminants. This process can help in the degradation of recalcitrant pollutants that are not directly used as a carbon or energy source by the bacterium. It's important to note that while Azospirillum can play a role in bioremediation, the success of any bioremediation strategy depends on various factors, including the type and concentration of pollutants, environmental conditions, and the presence of other suitable microorganisms. Bioremediation is often used in conjunction with other remediation techniques to achieve effective and comprehensive cleanup of contaminated sites. Additionally, the choice of the most suitable microorganisms for bioremediation depends on the specific contaminants and the environmental context, requiring careful assessment and monitoring throughout the process [66].

Hazardous substances can be reduced with Azospirillium biofertilizer without hindering plant development. As a result, the use of inexpensive biosorbent was suggested for the removal of heavy metals. Azospirillium biofertilizer has shown efficient removal of heavy metals such as copper (Cu) and chromium (Cr) in the studies. These substances effectively removed Cu and Cr at rates of 94% and 70%, respectively. Separation is adjustable for the removal of the desired material from effluent or other streams because it depends on the interaction between sorbent and sorbate. For both metals, parameter optimization including temperature, adsorbent dosage, duration, pH, and agitation rate was investigated [67]. Garcia et al. assessed the composition and variety of bacterial communities in petroleum-contaminated soil. Proteobacteria was the most prevalent phylum. The tested soils from both states were subjected to Next

Generation Sequencing (NGS) analysis, which demonstrated that this phylum had the highest relative abundance of all the discovered bacterial phyla. The heatmap divided the four samples into two groups based on the relative percentage of each genus found in each sample. In addition, this allowed us to recognize a large number of taxa, including *Skermanella sp., Azospirillum sp*., and unclassified species from the Rhodospirillaceae family, in alkaline soil from Tamaulipas [68].

Actinomycetes:

Actinomycetes are a group of filamentous bacteria that contribute to organic matter decomposition in the soil. They secrete enzymes that break down complex organic compounds, releasing nutrients for plant uptake. Actinomycetes also produce antibiotics that can suppress soil-borne pathogens and protect plants from diseases. Actinomycetes are gram-positive, aerobic, spore-forming bacteria that belong to the order Actinomycetales and are distinguished by aerial mycelium development on a substrate. They are the most prevalent organisms that create filaments that resemble threads in the soil and are in charge of giving newly churned, healthy soil its distinctively "earthy" fragrance. They play significant roles in the cycling of organic matter, they limit the establishment of several plant diseases in the rhizosphere, and they break down complex polymer combinations in dead plant, animal, and fungal material to produce a large number of extracellular enzymes that are beneficial to crop productivity. Actinomycetes are unique for their significant role in biological soil buffering, biological regulation of soil environments through nitrogen fixation, and breakdown of high molecular weight chemicals like hydrocarbons in contaminated soils [69]. By creating and stabilizing compost piles, creating stable humus, and collaborating with other soil microorganisms to break down tough plant and animal residues like cellulose, actinobacteria sustainably contribute to improving soil health. This helps to maintain the biotic equilibrium of the soil by assisting with nutrient cycling [70]. In a study carried out by Xie et a., the clearance rates of DDT and DDE were highest in the soil that had been seeded with ryegrass and inoculated with effective degrading strains of Actinomycetes. The soil's bacterial populations substantially rose, and bioremediation significantly enhanced microbial activity. The microbial population and diversity were greatly boosted by ryegrass, and phytoremediation had a greater impact on the variety and quantity of microbial species [71].

Xu *et al.* found that when organic fertilizer is applied along with actinomycetes inoculants, wheat dry mass in subterranean areas is increased, Cd buildup in these regions is reduced, and wheat stress resistance is improved. Actinomycetes can successfully be added to the microbial network to improve its complexity and contribute to the stability of the plant's inter-root microecology, which prevents the invasion of harmful bacteria. In addition to enhancing soil nutrients, this treatment significantly decreased wheat's Cd concentration. It has significantly increased the stability of plant rhizosphere microecology and could be a successful way to reduce soil Cd pollution [72]. The structure of the microbial population has an important role in an ecosystem's capacity to withstand severe changes. Agnihotri *et al.* used Phospholipid fatty acid analysis to look at the microbial population at the Municipal Solid Waste disposal site. They found a high titer of actinomycetes-containing microbes. It was concluded that the ability of the soil microbial population to withstand, recover from, and adapt to hazardous waste contamination may be determined using this approach, which can also be utilized to produce bioinoculants for the bioremediation of Municipal Solid Waste polluted sites [73].

Trichoderma fungi:

Trichoderma species are fungi that have biocontrol properties against various plant pathogens. They compete with and parasitize pathogenic fungi, preventing their growth and colonization. Trichoderma fungi can help suppress diseases such as damping-off, root rot, and wilt, promoting healthier plants and improved soil health [74]. Some Trichoderma species possess the ability to degrade or detoxify various environmental pollutants and contaminants. They can be used in bioremediation processes to help clean up polluted soils and improve the overall environmental quality [75]. Trichoderma fungi can trigger the plant's natural defense mechanisms, making them more resistant to abiotic stresses such as drought, salinity, and extreme temperatures. This can be particularly beneficial in soil restoration efforts, especially in degraded and challenging environments [76].

When it comes to biodegradation, using fungi to effectively remove hydrocarbon pollution from the soil is seen to be the superior alternative. To identify oil-decomposing fungus, soil samples from four distinct oil-contaminated soils were examined. Three species of *Trichoderma ie; T. viride, T. spirale, T. longibrachiatum* along with five other fungi were found in the oil-contaminated soils [77]. Trichoderma's remarkable metabolic capabilities can be used to make advancements in the bioremediation and biotransformation industries as well as in the evolution of degradation pathways. Restoration of the soil microbiota and bioremediation of the soil cover is crucial. A faster and quicker rate of solid waste breakdown is reported when many species or strains of Trichoderma are used in co-culture [78].

Yao *et al.* investigated the co-metabolism of benzo[a]pyrene (B[a]P) and *Trichoderma reesei* FS10-C's and its ability to bioremediate an old polycyclic aromatic hydrocarbon (PAH)-contaminated soil. The findings indicated that T. reesei FS10-C bioaugmentation would be a potential bioremediation approach for soils with a history of PAH contamination [79]. The chloronicotinyl insecticide imidacloprid, also known as I-[(6-chloro-3-pyridinyl)-methyl]-N-nitro-2-imidazolidinimine, has a half-life of more than 100 days in soil. *Aspergillus oryzae* and *Trichoderma longibrachiatumon*, two fungal isolates, were used to track the biodegradation of imidacloprid (20) ppm. The consortium mixed with bagasse and immobilized on agar discs was observed to have the maximum degradation of imidacloprid, which was estimated to be 99% [80]. From the mine tailings of Arabidopsis thaliana, two native fungi, *Mucor circinelloides,* and *Trichoderma asperellum*, were isolated, and were used to study the bioremediation processes of lead and cadmium-contaminated soil. According to the study, cadmium is more hazardous to plant development than lead, and inoculation with *Mucor circinelloides* and *Trichoderma asperellum* can increase A. thaliana's resistance to cadmium and lead by increasing root length and shoot fresh weight by 40.19–117.50% and 58.31–154.144%, respectively [81]. It was discovered that microbiologically-induced calcite precipitation is a workable, environmentally friendly technology for the bioremediation of As- and Pb-contaminated sites while researching the function of calcite, i.e., microbiologically-induced precipitate by ureolytic *Trichoderma sp.* MG, in the remediation of soils contaminated with arsenic (As) and lead (Pb) [82].

NaCl stress inhibits the absorption of critical elements in both roots and shoots; however, *Trichoderma harzianum* supplementation increased the uptake of essential elements. Compared to seedlings treated with NaCl alone, mustard seedlings treated with NaCl plus *Trichoderma harzianum* had reduced Na absorption. Through enhanced absorption of necessary nutrients, regulation of osmolytes, and antioxidants, *Trichoderma harzianum* demonstrated to be highly helpful in granting resistance to the mustard plants against NaCl stress [83]. Although using microorganisms to manage agricultural soil is an advantageous practice, many of them have failed when used on a big scale despite having considerable effects in the lab. Trichoderma is seen as a promising organism, nevertheless, not just for promoting plant growth and managing plant diseases, but also for mycorestoration and mycoremediation. There are connections between Trichoderma and the bioremediation of contaminants such as fungicides, insecticides, and heavy metals. To balance the energy resources and ecology, a thorough investigation of the use of Trichoderma for the restoration of salty, acidic, and metal-contaminated soil is also necessary [84]. A flowerpot experiment was used to examine the effects of using the native fungus *Trichoderma asperellum* and the plant *Suaeda salsa* together to remediate soil that has been co-contaminated with lead (Pb) and salt (Na+ and Ca2+). *T. asperellum* bioaugmentation of planted soil typically resulted in decreases in plant Pb, Na+, and Ca2+ concentrations and translocations of 9-42%, 13-58%, and 19-30%, respectively, as well as a 6-21% drop in soil Pb bioavailability. The shortcomings of the long-term remediation for salinity and heavy metals can be compensated for using this bioaugmentation-assisted phytoremediation approach [85].

The biodegradation of oil was studied using intentionally contaminated soil and the urea sorbent-biological product "Unisorb-Bio" with an immobilized mixed culture of *Trichoderma micromycetes* and Bacillus bacteria. The soil was then subjected to phyto-control using a test culture of cress salad. The oil content in the soil was demonstrated to drop by 10 times during the course of 9 weeks of exposure to "Unisorb-Bio" with immobilized oil-oxidizing strains, with the sowing quality (germination energy, seed germination) of cress-salad 72.5%. The outcomes show that even with a high level of initial pollution, "Unisorb-Bio" with immobilized microorganisms may heal the soil [86].

In Raiganj, Uttar Dinajpur, fungal isolates from several rhizospheric soil sites were gathered, identified, and tested for Ni, Cd, and Co resistance. To investigate their tolerance to heavy metals, six fungal isolates were chosen. The findings indicated that *Trichoderma aureoviride* TaN16 was the most tolerant fungus species, able to thrive at high Ni, Cd, and Co concentrations. Additionally discovered to have strong potential for heavy metal tolerance is *Trichoderma yunnanense* TaN17 [87]. It was noted that the existing state of current technology is still under progress, with numerous technological benefits already clarified and significant hurdles to be overcome, due to the extremely complicated nature of biotechnology associated with bioremediation via microbes. The number of issued or pending patents exhibited an upward trend, according to patent mapping. In this context, a large number of patent documents were found that describe techniques and procedures for preparing and using fungi in soil bioremediation, as well as advanced techniques involving genetic engineering and technology that employ consortia of various fungi and bacteria [88].

Bacillus and Pseudomonas bacteria:

Certain strains of Bacillus and Pseudomonas bacteria have been identified for their plant growth-promoting and disease-suppressive properties. They produce antimicrobial compounds, enzymes, and siderophores that inhibit the growth of pathogenic microorganisms and stimulate plant growth. These bacteria can improve nutrient availability, enhance root development, and provide protection against soil-borne diseases. Bacillus and Pseudomonas bacteria are instrumental in the bioremediation of soil

contaminated with various pollutants. Bacillus and Pseudomonas species are particularly well-suited for bioremediation due to their diverse metabolic capabilities and adaptability to different environmental conditions [89].
Bacillus and Pseudomonas bacteria can degrade a wide range of organic pollutants, including hydrocarbons (e.g., petroleum compounds, polycyclic aromatic hydrocarbons), pesticides, solvents, and other industrial chemicals. These bacteria produce specific enzymes that break down complex organic molecules into simpler, less toxic compounds [90]. Some strains of Bacillus and Pseudomonas can tolerate and sequester heavy metals and metalloids, such as lead, chromium, and arsenic. They can transform these toxic metals into less mobile and less bioavailable forms, reducing their environmental impact [91, 92]. Certain Pseudomonas species can fix atmospheric nitrogen and solubilize phosphorus, making these essential nutrients available to plants. This helps improve plant growth and enhances the overall bioremediation process by promoting vegetation that further contributes to soil stabilization and pollutant uptake. Bacillus and Pseudomonas can form biofilms, which are communities of microorganisms surrounded by a self-produced matrix. These biofilms provide a protected environment for the bacteria to thrive and facilitate the degradation of contaminants by concentrating and stabilizing the bacterial population [93].
Both genera are known for their adaptability to various environmental conditions, including those found in contaminated soils. They can survive and function under a wide range of pH levels, temperatures, and other challenging soil conditions, making them suitable candidates for bioremediation in diverse environments [94]. Bacillus and Pseudomonas species often work synergistically with other microorganisms in the soil to enhance the bioremediation process. The combined activities of different bacteria can lead to more efficient degradation and transformation of contaminants [95]. Bacillus and Pseudomonas can be introduced into contaminated soils either through bioaugmentation (adding specific bacteria to enhance biodegradation) or biostimulation (stimulating the growth and activity of existing soil microorganisms). Both approaches can significantly accelerate the bioremediation process [96].
Overall, Bacillus and Pseudomonas bacteria play crucial roles in the bioremediation of soil by breaking down organic pollutants, immobilizing heavy metals, promoting plant growth, and creating a conducive environment for the remediation process. The successful application of these bacteria for bioremediation depends on factors such as selecting appropriate strains, optimizing environmental conditions, and understanding the interactions between the bacteria and the contaminants present in the soil. These microorganisms can be applied to the soil through various methods, including seed coating, soil inoculation, composting, and organic amendments [97]. By reintroducing or enhancing populations of beneficial microorganisms, soil restoration efforts can improve soil health, nutrient availability, and disease suppression, leading to more productive and sustainable agricultural systems. Scientists are now concentrating on liquid biofertilizer technology, offering trustworthy justifications for their necessity and specificity.

Microbial Consortium:

Plant growth-promoting microorganisms have been identified as the potential means to increase crop yield while reducing the use of chemical fertilizers, pesticides, and fungicides, thereby reducing the harmful environmental impact of agriculture and maximizing the production of healthier and safer foods. When microorganisms of different groups form a consortium, they create synergies and work in a complementary manner, benefiting crops [98]. The combinations of plant growth-promoting bacteria, mycorrhizal fungi, and microbial biocontrol agents have been standardized for various plant species for cost-effective production (Table 2). Further optimization of plant-specific formulations of microbial consortium may prove to be a wonderful strategy for reducing the losses due to resistance to biotic and abiotic stresses and enhanced production and improved nutrient uptake [99].

Table 1. Role of Microorganisms in Soil Health Restoration

SN	Crop Plants	Functions	Reference
1.	Mycorrhizal fungi	Produce organic acids and glomalin, which reduce soil erosion, chelate heavy metals, enhance carbon sequestration, and stabilize soil macro-aggregation. Recruits bacteria releasing alkaline phosphatase, thus enhancing organic phosphorus availability. Influence the makeup, diversity, and activity of soil microbial populations.	[100]
2.	Rhizobium	Increase symbiotic N production Increase the production of defense chemicals Generate signals that govern stomatal function Release plant growth factors like; vitamins for plant defense and increased growth/productivity.	[101]

3.	Azospirillum	N Fixation Promotes plant development by conferring tolerance to biotic and abiotic stressors, by antioxidants, osmotic adjustment, phytohormone synthesis, and defense measures such as pathogenesis-related gene expression.	[102]
4.	Actinomycetes	Organic matter cycling, increase metabolite synthesis and encourage plant growth regulators. Limit the establishment of various plant diseases in the rhizosphere, biological buffering of soils. Breakdown complex polymer pollutants.	[103, 104]
5.	Trichoderma	Biocontrol by pathogen cell wall breakdown, competition for resources and space, and plant resistance development. Biofertilization and biostimulatory activity by generating phytohormones and the enzyme 1-aminocyclopropane-1-carboxylate deaminase.	[105]
6.	Bacillus	Acquisition of nutrients by organic matter decomposition, Production of phytohormones, Protection from pathogens and other abiotic stressors.	[106]
7.	Pseudomonas	Produces antagonistic chemicals such as cell wall breakdown enzymes and antibiotics for Induced Systemic Resistance. Synthesizes auxins which operate as signalling molecules in plant growth regulation.	[107]

Table 2. Microbial Consortium Formulated for Different Crop Plants

SN	Crop Plants	Microbial Consortium	References
1.	*Hordeum vulgare* L. *Helianthus annuus* L.	*Glomus intraradices*, *Glomus albidum*, *Glomus diaphanum*, and *Glomus claroideum*	[108]
2.	*Jatropha curcas*	*Azotobacter chroococcum* and arbuscular mycorrhizal fungi (AMF)	[109]
3.	Rice (*Oryza sativa*)	Non-rhizobial endophytic microbes isolated from a macrophyte *Typha angustifolia*	[110]
4.	Climbing bean (*Phaseolus vulgaris* L.)	Nine native rhizobia isolates	[111]
5.	Maize (*Zea mays)*	Rhizobium species isolated from nodules of Lentil (*Lens culinaris* M.) Chickpea (*Cicer arietinum* L.)	[112]
6.	*Capsicum annuum*	Arbuscular mycorrhizal fungal species isolated from the rhizosphere of *C. annuum*	[113]
7.	*Pisum sativum* L.) mutant SGECd^{t}	Rhizobacterium *Variovorax paradoxus* 5C-2, nodule bacterium *Rhizobium leguminosarum* bv. *viciae* RCAM1066, and arbuscular mycorrhizal fungus *Glomus* sp. 1Fo	[57]
8.	*Coffea arabica*	Arbuscular mycorrhizal fungi consortia	[114]
9.	*Cicer arietinum* L.	Rhizobacteria (*Pseudomonas* sp., *Burkholderia* sp. *Mesorhizobium* sp.) and arbuscular mycorrhizal fungi (AMF) (*Rhizophagus irregularis, Funneliformis geosporum, Claroideoglomus claroideum*)	[115]
10.	Wheat	Bacillus sp. and arbuscular mycorrhizal fungi	[116]
11.	Tomato and Lettuce	*Penicillium pinophilum* and Three AMF species *(Rhizophagus irregularis, Rhizophagus intraradices, and Claroideoglomus etunicatum)*	[117]
12.	Urdbean (*Vigna mungo* L)	*Rhizobium sp.* (PUR-34 and A-3) and two PGPRs (*Stenotrophomonas rhizophilia* PUK-171 and *Nanobacterium sp.,* PUK-46B6)	[118]
13.	Soybean	*Streptomyces sp.* strain ASR 58 and *Streptomyces sp.* strain ASR 67,	[119]

CONCLUSION

It can be concluded from the presented study that bioremediation is a sustainable and environmentally acceptable method to manage environmental problems and improve agricultural output by using microorganisms for environmental clean-up and soil restoration. We can encourage healthier ecosystems, lessen pollution, and promote sustainable agricultural practices for a more resilient and environmentally friendly future by encouraging positive interactions between microbes and plants. A number of microbial consortiums have been tested for better plant growth and maximum production. This study will help researchers conduct more experiments to optimize the best formulation specific to a particular crop plant.

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